The vertexing challenge at FCC-ee

11th International Workshop on Semiconductor Pixel Detectors for Particles and Imaging, Strasbourg

Armin Ilg[1] Anna Macchiolo[1] Fabrizio Palla[2]
on behalf of FCC

[1]University of Zürich
[2]INFN Pisa

21.11.2024

The Future Circular Collider (FCC) integrated programme

Circular collider with 90.7 km circumference machine to serve HEP for the rest of the century

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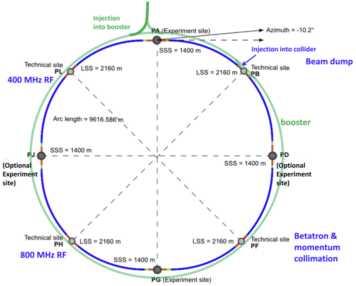
FCC-ee: e^+e^- collisions at highest luminosities → *intensity frontier*



Schematic layout of FCC-ee [1]

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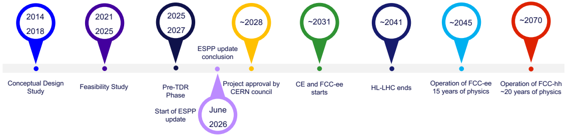

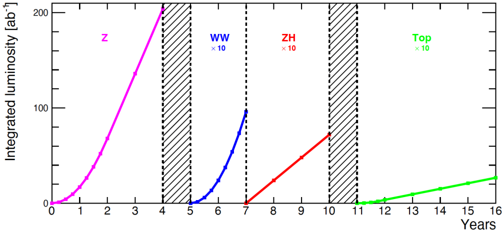

Possible FCC-ee run plan [2]

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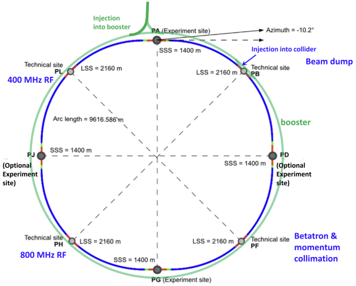

Schematic layout of FCC-ee [1]

EW: $2.4 \cdot 10^8$ WW, $6 \cdot 10^{12}$ Z
Flavour: $O(10^{12})$ $b\bar{b}$, $c\bar{c}$, etc., $O(10^{11})$ $\tau\bar{\tau}$
H: $1.78 \cdot 10^6$ HZ, 125k WW → H
Top: $1.9 \cdot 10^6$ $t\bar{t}$

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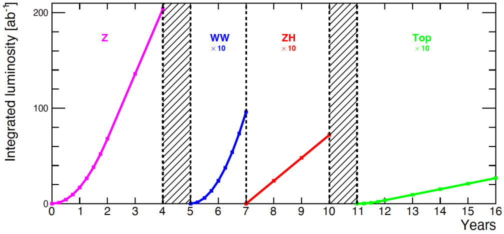

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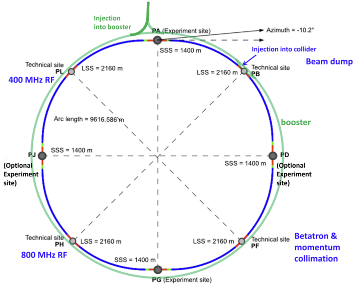

Schematic layout of FCC-ee [1]

EW: $2.4 \cdot 10^8$ WW, $6 \cdot 10^{12}$ Z ← **challenging!**
Flavour: $O(10^{12})$ $b\bar{b}$, $c\bar{c}$, etc., $O(10^{11})$ $\tau\bar{\tau}$
H: $1.78 \cdot 10^6$ HZ, 125k WW → H
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Need to match tiny statistical uncertainties with theoretical and experimental systematic uncertainties of $\mathcal{O}(10^{-4}$–$10^{-5})$!

FCC-ee detector *concepts* + variations (RICH, different trackers, ...)

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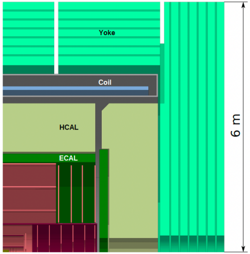
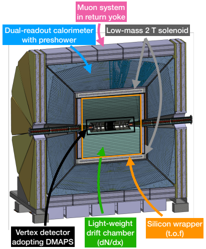


CLD [3, 4]/ILD' [5]



IDEA [6, 7]

ALLEGRO [8]

CLD/ILD'

- ILC (→ CLIC) → FCC-ee (→ μCol)
- Si vertexing and Si tracking/TPC
- Highly-granular ECAL and HCAL, CALICE-like
- Solenoid coil outside calorimeter system

IDEA

- Si vertexing
- Drift chamber (down to 1.6% X_0, $dN_{ion.}/dx$)
- Silicon wrapper with T.O.F
- Crystal ECAL, light solenoid, dual-readout calorimeter
- μ-RWELL muon detector in return yoke

ALLEGRO

- Si vertexing
- Drift chamber, silicon wrapper
- Noble liquid ECAL, Pb/W+LAr or W+LKr
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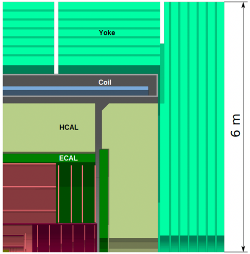

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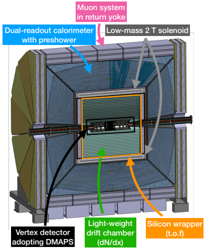

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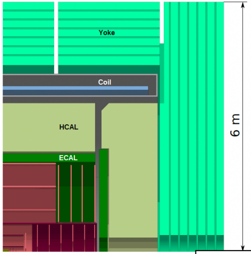

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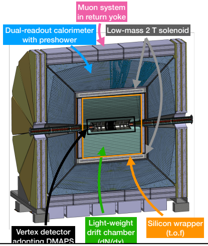

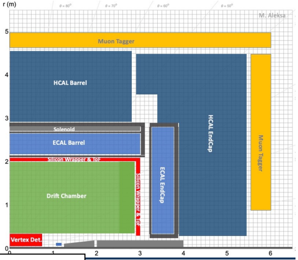

ALLEGRO [8]

All foreseeing Monolithic Active Pixel Sensors (MAPS)!

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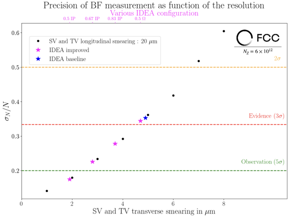
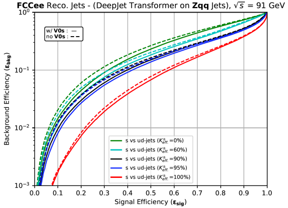
The need for precise vertex reconstruction

For anything that has secondary vertices!

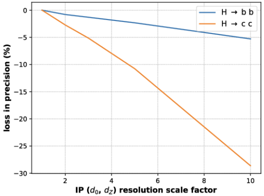
- b and c hadrons, taus, V0s, ...
- Reconstruct complex decay chains
- Particle lifetime measurements
- Efficient flavour tagging (b/c/g/**s**)



$B^0 \to K^{*0}\tau^+\tau^-$ [9]



Secondary vertices for *s*-tagging [10]



Impact of IP resolution on Yukawa coupling measurement (L. Gouskous)

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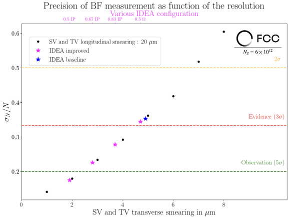

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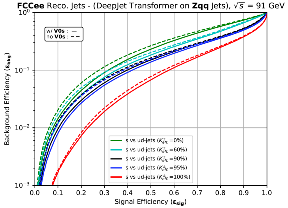
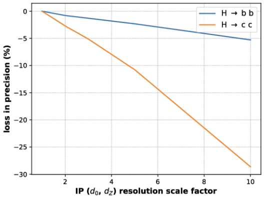


Secondary vertices for s-tagging [10]

Stringent requirements on vertex detector to limit syst. uncertainties:

→ Coverage down to $|\cos(\theta)| \lesssim 0.99$ and high reco. efficiency

→ $\sigma_{d_0} = a \oplus \frac{b}{p \sin^{3/2}\theta}$ with $a \approx 3\,\mu\text{m}$, $b \approx 15\,\mu\text{m}\text{GeV}$



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University of Zurich[UZH]

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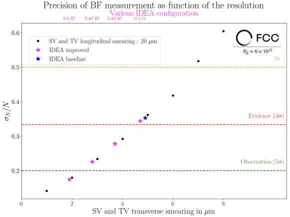

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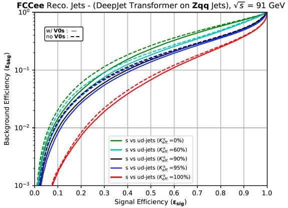

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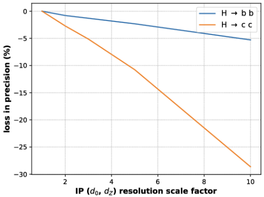
Challenges and resulting requirements to overcome them

- a given by sensor resolution → Small single-hit resolution, pixels
- b given by *multiple scattering* → Minimise material budget (number of radiation lengths X_0) in vertex and beam pipe
  - → Also relevant for momentum resolution in tracker

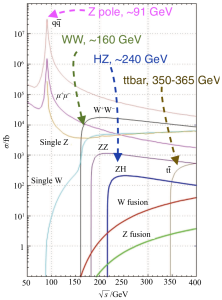


Impact of IP resolution on Yukawa coupling measurement (L. Gouskous)

FCC-ee collision environment at the Z pole

☺: e^+e^- collisions are *clean* - there's no QCD in the initial state

☹: Very high inst. luminosity of $140 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ thanks to 50 MHz bunch collision rate ($t_{BC} = 20\,\mathrm{ns}$)



e^+e^- annihilation cross section [11]

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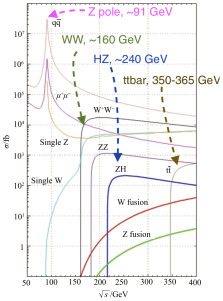
- Very high rate of interesting events (200 kHz of Z) that need to be read out and saved (and simulated!)
- Considerable beam backgrounds, mainly from incoherent pairs
  - Hit rate of $\mathcal{O}(200\,\mathrm{MHz/cm}^2)$ for innermost layer

  → Trigger-less readout will be challenging
- "Pile-up" of 200 kHz/50 MHz = 0.004 at Z-pole

  → Integrate over of a couple of bunch crossings?

  → But need to check impact on uncertainties
  - Timing of $\mathcal{O}(\text{few ns} - 1\,\mu\text{s})$
- $\mathcal{O}(1 \times 10^{14}\ 1\,\mathrm{MeV}\ n_{\mathrm{eq}}\mathrm{cm}^{-2})$ and $\mathcal{O}(10\,\mathrm{MRad}/100\,\mathrm{kGy})$ per year



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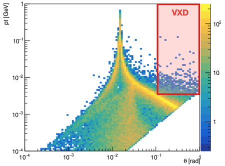

Incoherent pairs at Z pole [12]

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How do the detector concepts realise such a vertex detector?

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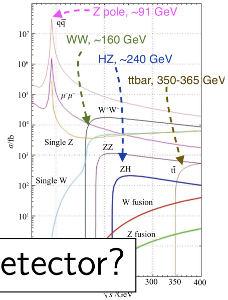

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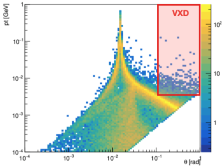


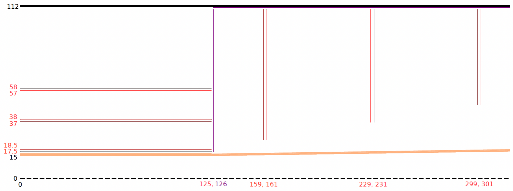
Incoherent pairs at Z pole [12]

FCC-ee vertex concept developments

FCC-ee vertex detector layouts

University of Zurich[UZH]

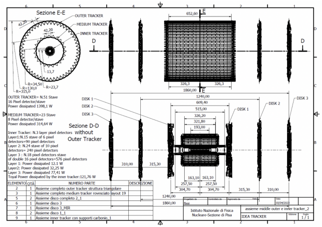
CLD → Rescaled CLICDet vertex detector



CLD vertex detector layout [3]

- $r_{\mathrm{min}} = 13\,\mathrm{mm}$
- Three double-layer barrel layers and disks, 0.6–0.7% X_0 per double layer
- No engineering studies since CLICDet developments
- No specific sensor chosen, assume 3 μm single-point resolution

IDEA → Original FCC-ee vertex layout



→ Also currently used for ALLEGRO detector concept

- $r_{\mathrm{min}} = 13.7\,\mathrm{mm}$
- Three inner barrel single-layers (0.25% X_0), two outer barrel layers and three disks
- Engineered design integrated into machine-detector interface region (INFN-LNF [13])
- Baseline: ARCADIA [14] (inner barrel, $25 \times 25\,\mu\mathrm{m}^2$) and ATLASPix3 [15] (outer barrel and disks, $150 \times 50\,\mu\mathrm{m}^2$) sensors

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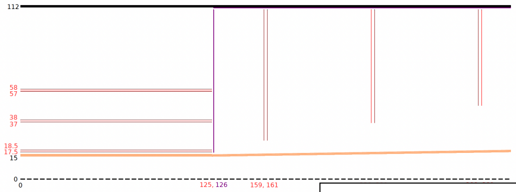

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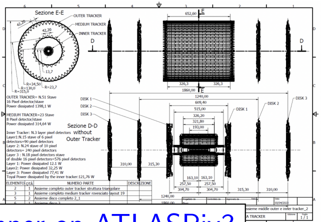

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See poster of M. Hübner on ATLASPix3

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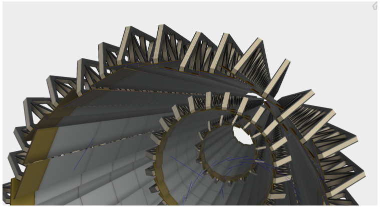
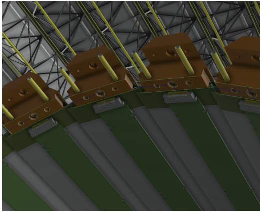
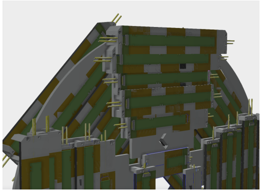
Vertex detector by INFN Pisa

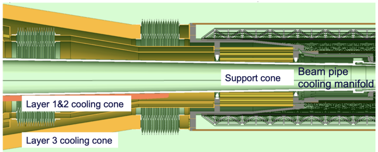


Inner vertex barrel with dual modules of ARCADIA, air-cooled → $\lesssim 50\,\mathrm{mW\,cm^{-2}}$

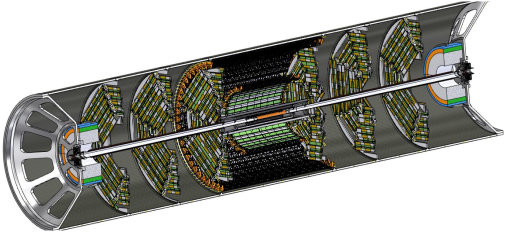




Outer vertex barrel and disks using quad ATLASPix3 DMAPS with $150 \times 50\,\mu\mathrm{m}^2$ pixels, water-cooled



Inner vertex support and cooling cones, first air cooling and transient mechanical analysis results promising



Support tube holding lumical, vertex and beam pipe

University of Zurich[UZH]

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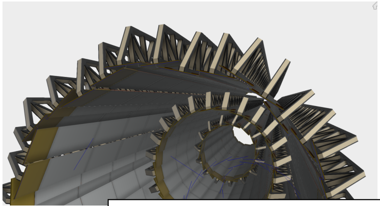
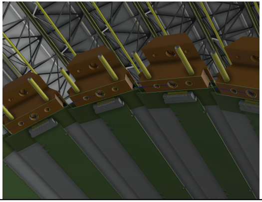
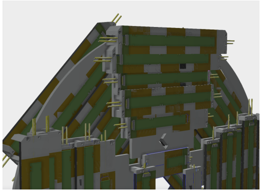




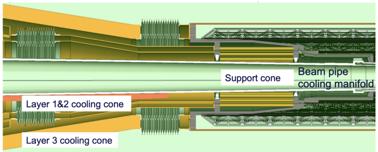


More details on vertex integration in MDI in F. Palla's poster

Inner verte[x] ... of ARCADI[A], air-cooled ... $\lesssim 50\,\mathrm{mW\,cm^{-2}}$

... pixels, water-cooled

... $\times 50\,\mu\mathrm{m}^2$



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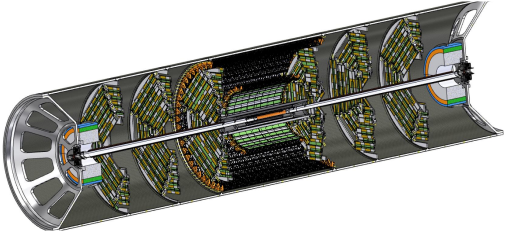
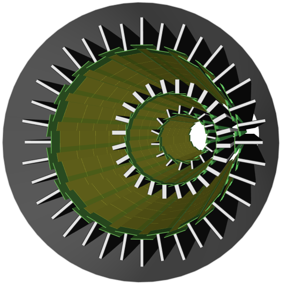
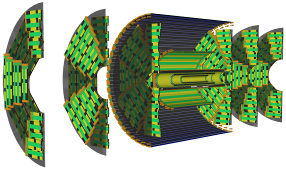


Support tube holding lumical, vertex and beam pipe

IDEA vertex detector full simulation model



Inner vertex barrel in DD4hep

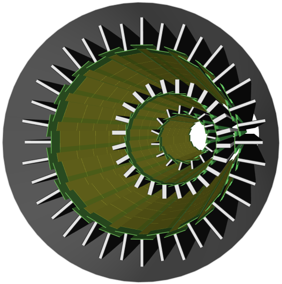


Complete vertex in DD4hep

- Accurate description of engineered vertex detector
- Taking into account on-detector services and supports

IDEA vertex detector full simulation model

University of Zurich[UZH]



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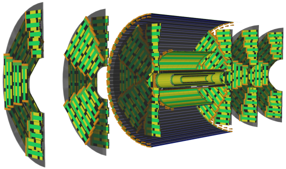
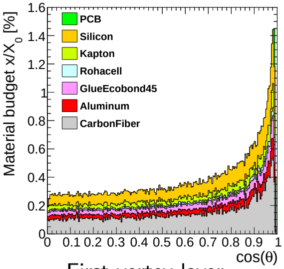


Complete vertex in DD4hep

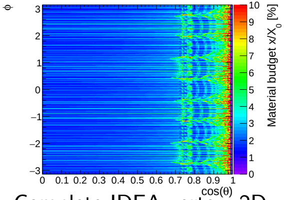
- Accurate description of engineered vertex detector
- Taking into account on-detector services and supports
- Realistic material budget evaluation

→ Compatible with CDR assumption

→ $\approx 0.25\%\ X_0$ at $\cos(\theta) = 0$ for first layer, $\approx 2\%$ for complete vertex

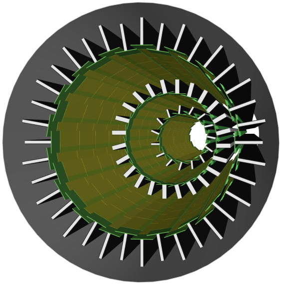


First vertex layer



Complete IDEA vertex, 2D

IDEA vertex detector full simulation model



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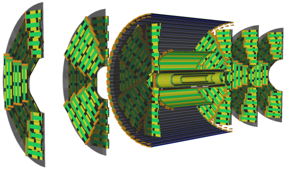

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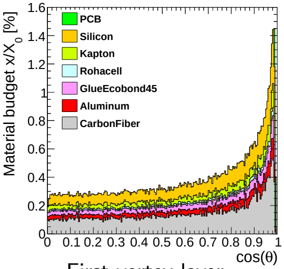
→ Compatible with CDR assumption

→ $\approx 0.25\%$ X_0 at $\cos(\theta) = 0$ for first layer, $\approx 2\%$ for complete vertex

- Correct description of sensor peripheries

→ Allows for more realistic vertex performance estimation than CLD vertex or previous fast simulation studies (Delphes)



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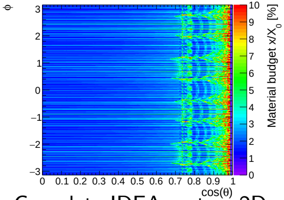
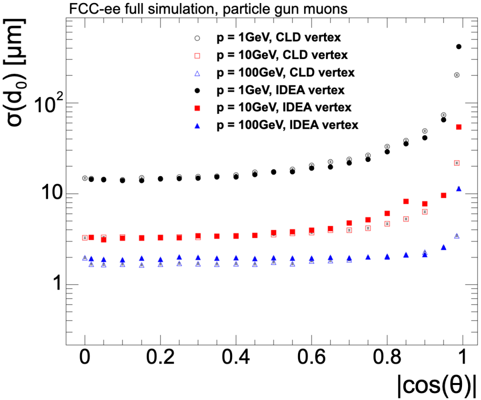


Complete IDEA vertex, 2D

IDEA vertex detector performance

Use CLD with CLD reconstruction (from iLCSoft, inside Key4hep), and replace the vertex. Plotting with k4DetPerformance.



CLD vs. IDEA vertex, 1D

- CLD vertex better at high p, IDEA better for low p
  - → CLD uses double layers (with double the material)

N.B: Non-optimised reconstruction for IDEA vertex!

IDEA vertex detector performance

University of Zurich[UZH]

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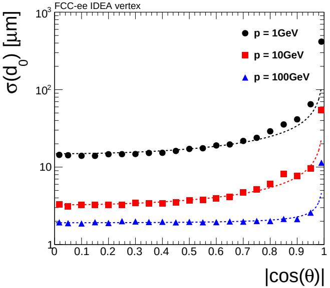
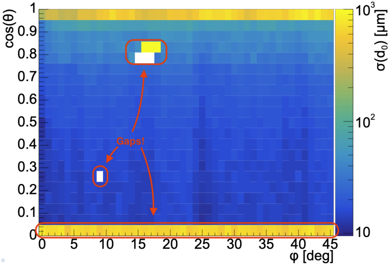


IDEA vertex with $a \oplus \frac{b}{p \sin^{3/2}\theta}$ fit



σ_{d_0} for different ϕ at 1 GeV. Semester project of K. Mirbaghestan (UZH, [16])

- CLD vertex better at high p, IDEA better for low p
  - → CLD uses double layers (with double the material)
- Quite uniform σ_{d_0} along ϕ in IDEA ($\pm 20\%$)
  - Coverage down to $|\cos(\theta)| \lesssim 0.99$
- Gaps in coverage found
  - → Due to 200 μm space between sensors
  - → To be fixed soon!

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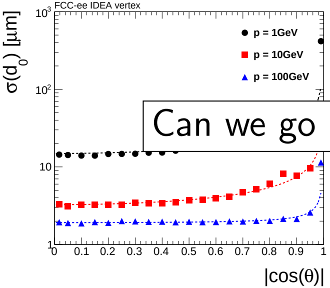

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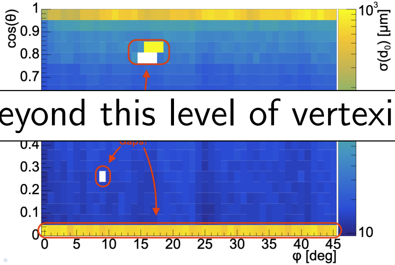

σ_{d_0} for different ϕ at 1 GeV. Semester project of K. Mirbaghestan (UZH, [16])

Can we go beyond this level of vertexing performance?

- CLD vertex better at high p, IDEA better for low p
  - → CLD uses double layers (with double the material)
- … d_0 along ϕ in IDEA ($\pm 20\%$)
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Physics use-case for better vertex detector performance

University of Zurich[UZH]

- Four trillion $e^+e^- \rightarrow Z \rightarrow q\bar{q}$ collisions at FCC-ee $\rightarrow$ *Flavour factory*
- Are B hadrons decaying in the same way to all leptons? $\rightarrow$ *Lepton flavour universality/violation*

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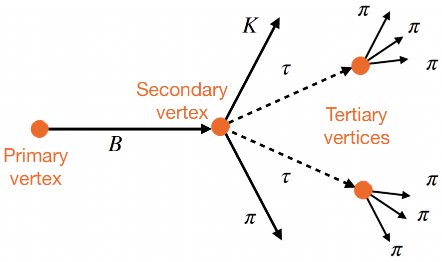
- $B^0 \to K^{*0} + \tau^+ + \tau^-$ not observed yet, limit of BR $< \mathcal{O}(10^{-3}$–$10^{-4})$
  $\to$ but SM value at 10^{-7}, strongly enhanced in many beyond SM theories!



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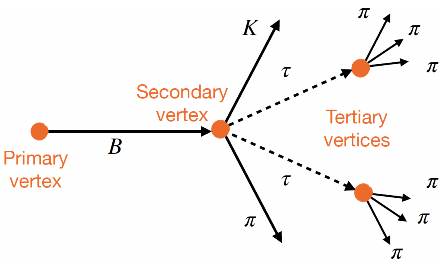


$\to$ More precise vertex reconstruction crucial to reconstruct B^0 mass and distinguish from backgrounds

- Close to evidence (3σ) using current IDEA baseline in Delphes fast simulation study (T. Miralles et al. at FCC Physics Workshop 2024, [9])

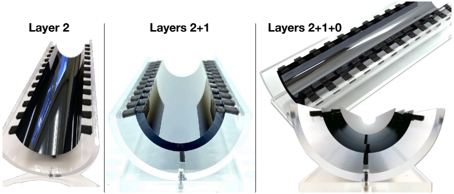
$\to$ Need to improve SV and TV resolution by ~ 2 to have chance at discovery $\to$ Improve single-hit resolution and **material budget**!

Ultra-light vertex detectors for FCC-ee

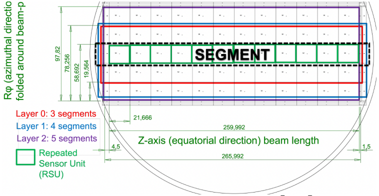
Sensor-only vertex detector

DMAPS in 65 nm TPSCo process

- More logic per cm^2 → More functionality/smaller pixels
- Low power consumption → Helps air cooling
- Enables 12" wafers → Large, bent sensors!



Layer assembly concept for ALICE ITS3 [17]



MOSAIX wafer layout [18]

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University of Zurich[UZH]

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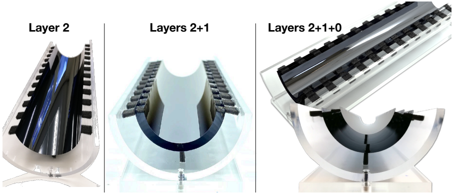

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F. Reidt's and L. Terlizzi's talks
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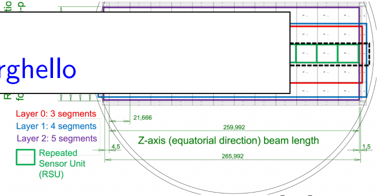

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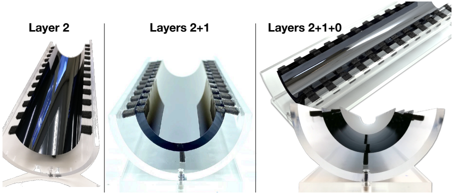
	ALICE ITS3	FCC-ee
r_{min} [mm]	19	~ 13
$\lvert\cos(\theta)\rvert$ coverage until	0.97–0.99	0.99
Single-hit resolution [μm]	5	3
Part. hit density at r_{min} [MHz/cm^2]	8.5	250 ?



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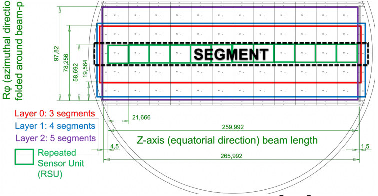

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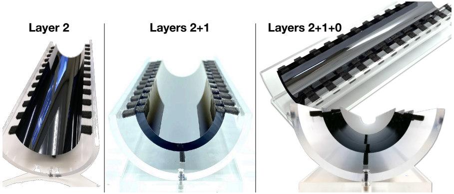

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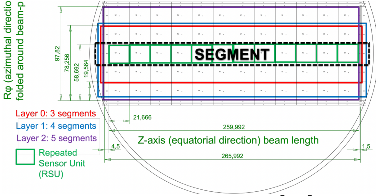


MOSAIX wafer layout [18]

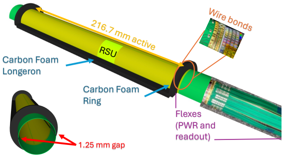
- First layer at smaller radius $\rightarrow$ Use just two segments
- Forward-backward asymmetries measurements $\rightarrow$ Read and power from both sides
- Forward coverage $\rightarrow$ Multiple sensors in a row at larger r
- Tight hermiticity requirement at FCC-ee, but have $\sim 5\%$ insensitive periphery in sensor and difficult to overlap sensors
  $\rightarrow$ Four layers ensures ≥ 3 hits in vertex, minimise periphery

Ultra-light inner vertex concept for FCC-ee

University of Zurich[UZH]

Layer 1 and 2

- 10 and 13 repeated sensor units long → $|\cos(\theta)| < 0.992/0.99$
- Peripheries, gap between half-barrels → Rotation in ϕ to fill gaps
- Readout and power from both sides

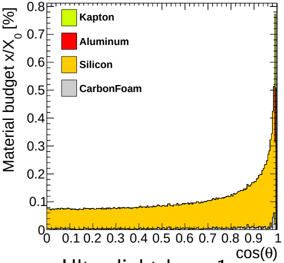


Layer 1 layout

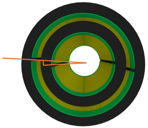
Layer 3 and 4

- Two sensors per side, readout only on sides, power on sides and centre (power wire)
- 8 (10) RSUs on +z (-z) side for layer 3, inverted for layer 4
  → $|\cos(\theta)| < 0.991/0.986$

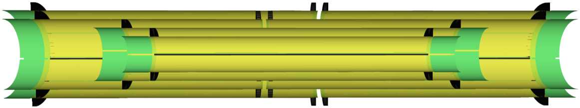
Assume 50 μm of Si + 16 μm of Si-equivalent (metal layer along sensor)



Ultra-light layer 1



Layer 1+2 front

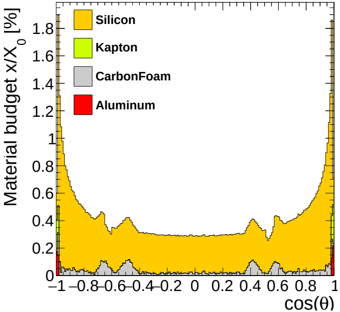


Longitudinal cross section of all four layers

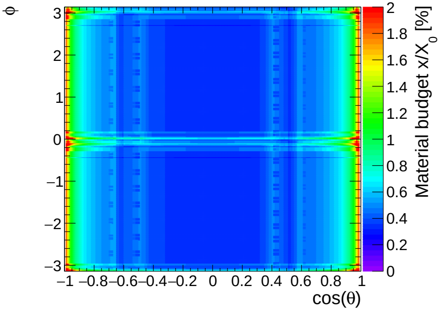
0.075% X_0 at $\cos(\theta) = 0$

→ factor 3.3 improvement!

Ultra-light inner vertex concept: Discussion



Complete ultra-light inner vertex, 1D



Complete ultra-light inner vertex, 2D

→ Almost same material budget as one layer (!) of normal IDEA vertex

→ More uniformly in ϕ

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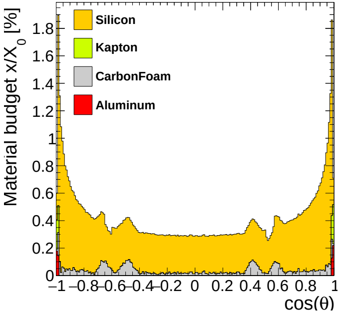

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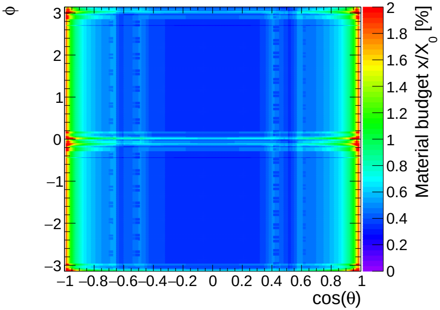

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→ Started engineering layout

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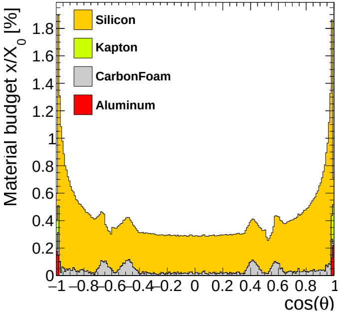

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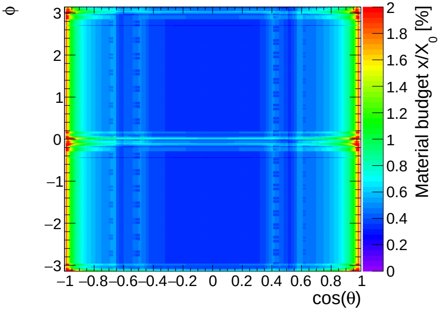

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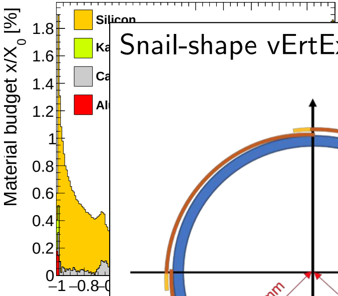

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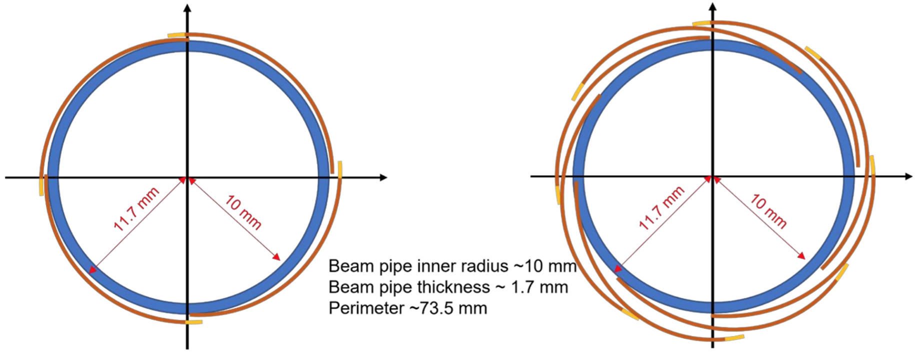
Snail-shape vErtEx Detector (FCC-SEED) proposal by IPHC Strasbourg



A. Besson at 3rd ECFA HET workshop

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Summary of requirements and how to fulfill them

Physics challenges	Requirement
Coverage down to $\lvert\cos(\theta)\rvert \lesssim 0.99$	Long barrel, forward disks
High reconstruction efficiency	Hermetic layers, small peripheries, $> 99\%$ hit eff., more layers?
Asymptotic resolution of $a \approx 3\,\mu m$	$3\,\mu m$ single-hit resolution, small r_{min}
Multiple scattering: $b \approx 15\,\mu m\,GeV$	• light beam pipe • $\leq 0.3\%\ X_0$/layer $\rightarrow$ thin sensors, air-cooling, light support

Summary of requirements and how to fulfill them

University of Zurich[UZH]

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Collision environment challenges	Requirement
High luminosity	• Save events at $\geq 200 kHz$ • With trigger or without
Avoid pile-up of Z's	Integration time $\lesssim 1\,\mu\text{s}$
Beam backgrounds	Hit rate capability up to $\mathcal{O}(200\,\text{MHz/cm}^2)$
Radiation environment	$\mathcal{O}(1 \times 10^{14}\ 1\,\text{MeV}\ n_{\text{eq}}\text{cm}^{-2})$ and $\mathcal{O}(100\,\text{kGy})$ per year

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Advanced challenges	Requirement
≈ 2 reduction of σ_{d_0}	Smaller spatial resolution and r_{min}, lighter vertex and beam pipe
Bunch tagging/inner T.O.F reference	$\mathcal{O}(20\,\text{ns})$ time resolution/$\mathcal{O}(10\text{'s of ps})$

Personal selection of existing MAPS

University of Zurich[UZH]

MOSAIX/ALICE ITS3 [18]

- 65 nm TPSCo
- $20.8 \times 22.8\,\mu m^2$ pitch
- $40\,mW/cm^2$ in pixel matrix ($1000\,mW/cm^2$ in periphery)
- $\mathcal{O}(10\,MHz/cm^2)$
- Wafer-scale
- Integration time down to $2\,\mu s$

ARCADIA [14]

- 110 nm LFoundry
- $25 \times 25\,\mu m^2$ pitch
- $\sim 30\,mW/cm^2$
- Up to $100\,MHz/cm^2$ (post-layout simulations)
- $1.28 \times 1.28\,cm^2$, side-abuttable
- Time resolutions from $\mathcal{O}$(ns) to $\mathcal{O}$(10's of ps)

No MAPS exists yet that can fulfil all FCC-ee vertex requirements simultaneously, but many starting and ongoing projects in this direction!

$\rightarrow$ Z. El Bitar's talk and A. Lorenzetti's poster on CE-65 and Y. Zhang's talk on TaichuPix

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DRD3 project on 65 nm MAPS for vertexing

- *Fine-Pitch CMOS Sensors with Precision Timing for Lepton Collider Experiments* [19]

→ Name soon to be finalised

Conclusions

University of Zurich[UZH]

FCC-ee poses **tight requirements** to its vertex detector

- The combination of all the requirements is the challenge
  - → Material budget as antagonist to all other requirements
- Opportunities thanks to novel technologies like embedded FPGA, wireless readout, and many more start to be explored

Detailed **design and engineering** studies starting

- CAD design, integrated into MDI, and detailed full simulation description
- Reasonable σ_{d_0} performance of IDEA vertex using CLD detector and reconstruction
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Ultra-light inner vertex detector concept

- Conceptual design, adapted from ALICE ITS3 to FCC-ee
- Compromise hermeticity (or radius of first hit) with reduced material budget
- Evaluate performance similarly to IDEA vertex

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- CAD design, integrated into MDI, and detailed full simulation description
- Reasonable σ_{d_0} performance of IDEA vertex using CLD detector and reconstruction
  - → More work on digitisation and integration with gaseous trackers needed

Ultra-light inner vertex detector concept

- Conceptual design, adapted from ALICE ITS3 to FCC-ee
- Compromise hermeticity (or radius of first hit) with reduced material budget
- Evaluate performance similarly to IDEA vertex

Final goal: **Global detector optimisation**

→ Smallest possible experimental systematic uncertainty

Thanks!

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Co-project Manager: Magnus Mager, magnus.mager@cern.chds.

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CLD with IDEA vertex detector

Necessary changes

- Removing first Inner Tracker barrel layer ($r = 127\,\text{mm}$)
- Removing first and second Inner Tracker disks ($r = 79.5$ and $123.5\,\text{mm}$)
- Increase conformal tracking max. distance (CT_MAX_DIST)
- *MinClustersOnTrack* from 4 to 3 in conformal tracking in vertex barrel and disks

Nota bene

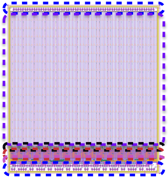
- No silicon wrapper
- Assume spatial resolution of $3\,\mu\text{m}$ for inner vertex barrel (same as CLD), and $14\,\mu\text{m} \times 43\,\mu\text{m}$ for outer barrel and disks (CLD: vertex endcap: $3\,\mu\text{m}$, inner tracker endcap: $5\,\mu\text{m}$ or $7 \times 90\,\mu\text{m}$)

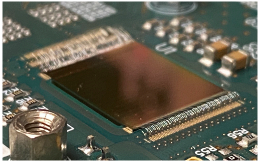
Definitely not perfect, but works, reasonable performance

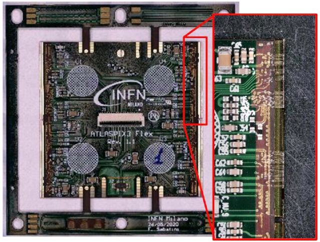
IDEA vertex detector: ARCADIA and ATLASPix3

Depleted Monolithic Active Pixel Detectors

- **Inner Vertex (inspired to ARCADIA):**
  - Lfoundry 110 nm process
  - *50 μm thick, 25 μm x 25 μm*
  - Module dimensions: $8.4 \times 32\ mm^2$
  - Power density $50\ mW/cm^2$ (core $30\ mW/cm^2$)
  - **Current at 100 MHz/cm²**
- **Outer Vertex and disks (inspired to ATLASPIX3)**
  - TSI 180 nm process
  - *50 μm thick (50 μm x 150 μm)*
  - Module dimensions: $42.2 \times 40.6\ mm^2$
  - Power density: assume $100\ mW/cm^2$
  - **Up to 1.28 Gb/s downlink**

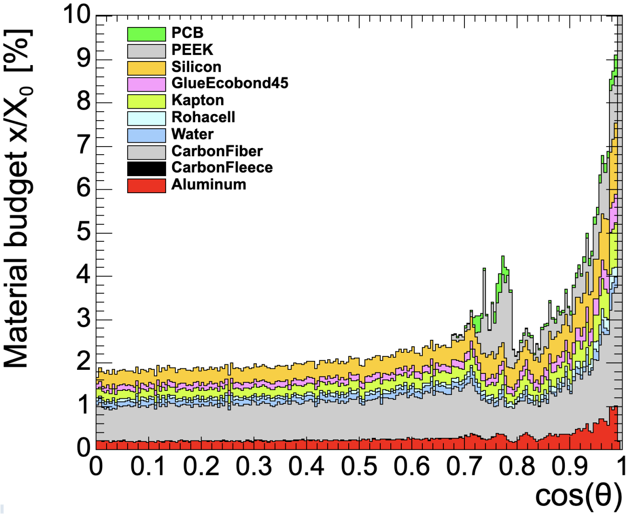






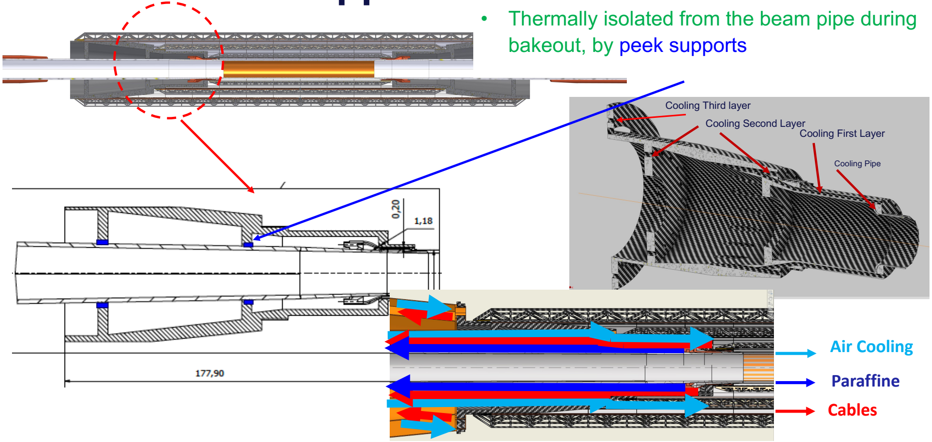
F. Palla, 2nd FCC US workshop at MIT

Only contribution in last two bins



Inner Vertex support

- Anchored to the conical chamber
- Air cooled
- Thermally isolated from the beam pipe during bakeout, by peek supports

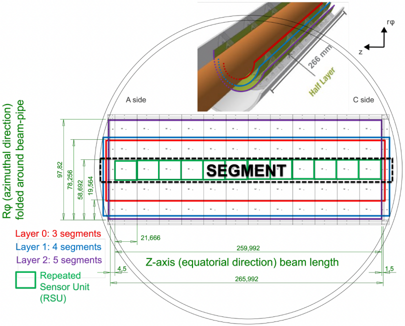


F. Palla, 2nd FCC US Workshop

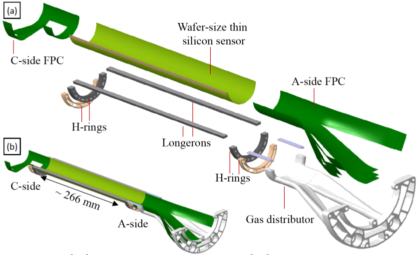
ALICE ITS3 layout

University of Zurich[UZH]

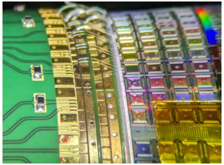
- Three layers of wafer-scale 65 nm MAPS
- Building blocks are Repeated Sensor Units (RSUs) that are stitched together
  - 12 RSUs in z direction
  - 3, 4 or 5 segments around ϕ
- Data transmission in sensor along z
- Metal layer for distribution of power
- Endcaps on sides for powering and readout
- Air-cooling from one side



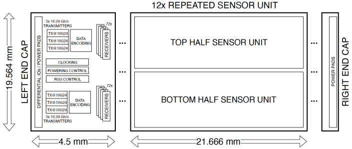
Wafer stitching plan [18]



Exploded (a) and assembled (b) ITS3 half-layer[18]

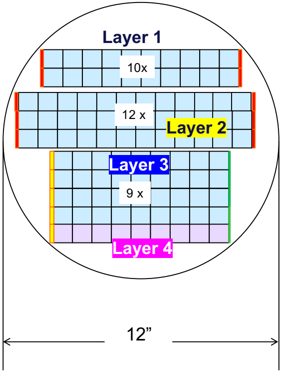


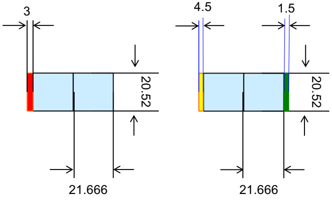
Wire bonds from sensor to FPCs [18]



Block diagram of sensor segment [18]

Same reticle for all layers





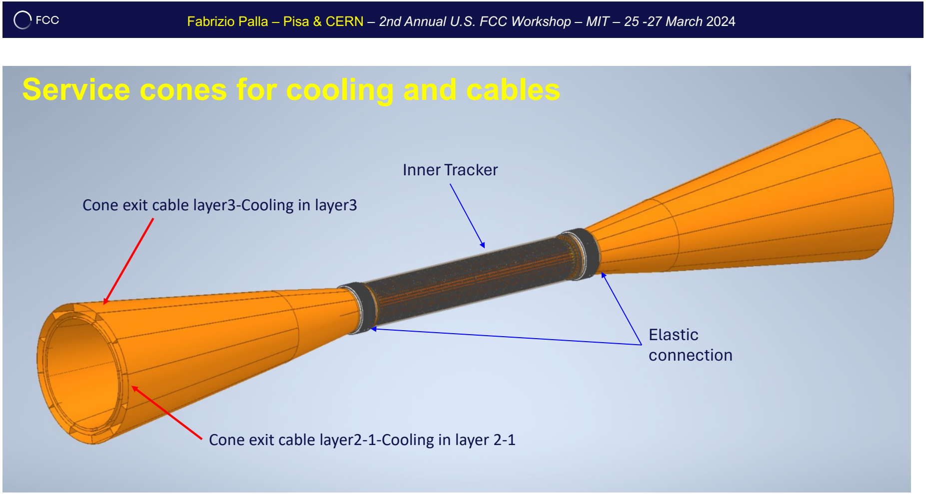
Layer 1&2 **Layer 3&4**

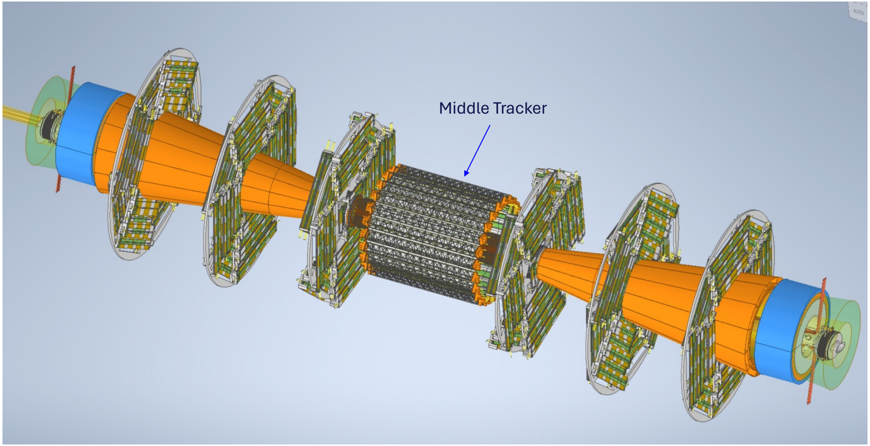
Layer	Radius (mm)
1	13.7
2	20.23
3	26.76
4	33.3

	Power density $[\mathrm{mW\,cm^{-2}}]$		
	Expected 25 °C	Max 25 °C	Max 45 °C
Left End Cap (LEC)		791	
Active area (RSU)	28	44	62
Pixel matrix	15	32	51
Biasing	168	168	168
Readout peripheries	432	457	496
Data backbone	719	719	719

Power dissipation in ITS3
(not necessarily the same for FCC-ee)

- RSU~ 50 mW/cm^2 (depends on Temp.)
- LEC ~ 700 mW/cm^2

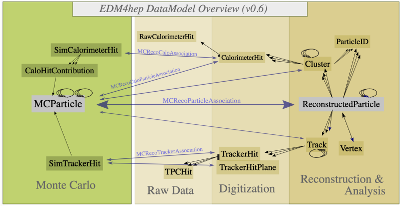

FCC
Fabrizio Palla – Pisa & CERN – 2nd Annual U.S. FCC Workshop – MIT – 25 -27 March 2024
Service cones for cooling and cables
Inner Tracker
Cone exit cable layer3-Cooling in layer3
Elastic connection
Cone exit cable layer2-1-Cooling in layer 2-1

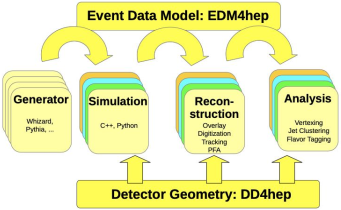

Middle Tracker

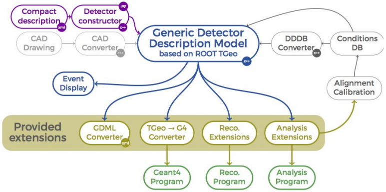
The common software vision: Key4hep

Key4hep is a huge ecosystem of software packages adopted by all future collider projects, complete workflow from generator to analysis

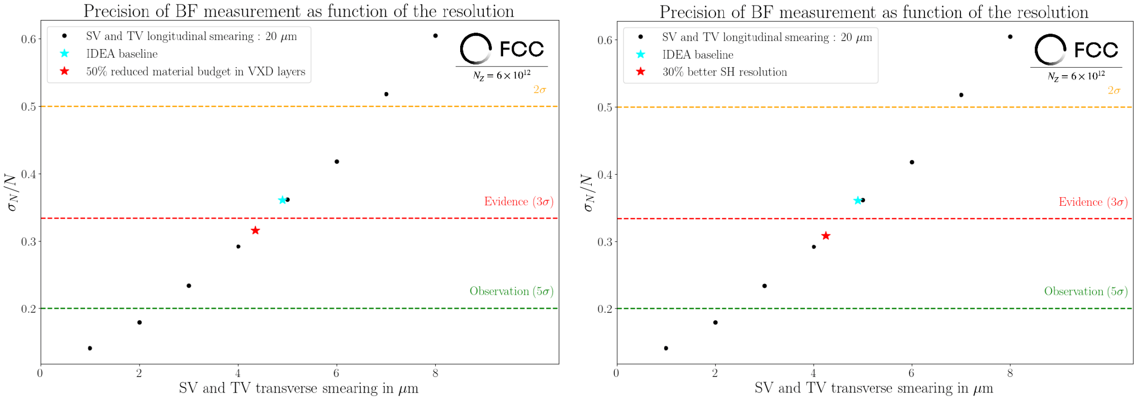
- Event data model: EDM4hep for exchange among framework components
  - Podio as underlying tool, for different collision environments
  - Including truth information
- Data processing framework: Gaudi
- Geometry description: DD4hep, ability to include CAD files
- Package manager: Spack: `source /cvmfs/sw.hsf.org/Key4hep/setup.sh`







$B^0 \to K^* + \tau^+\tau^-$: Impact of material budget and resolution



Tristan Morales at 7th FCC Physics Workshop